STRUCTURE AND FRACTURE FEATURES OF Ti-Si- AND Ti-B-BASED IN SITU COMPOSITES

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“Metallic Materials with High Structural Efficiency”

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- **Introduction**
- **Materials and methods**
- **Experimental results and their discussion**
  - ***Structure***
  - ***Fracture mechanisms***
- **Conclusions**

Introduction - I

- Ti-based in-situ composites are considered as structural materials attractive for aerospace industry.
- At acceptable level of strength (1-1.5 GPa) Ti-based in-situ composites are brittle in as-cast state however being plastically deformed they demonstrate suitable ductility (>2%).

Introduction – II

Lack of systematic studies
on their structure and its influence
on mechanical behavior
especially fracture mechanisms
at a brittle-to-ductile transition.

Objectives:

to get answers

1. **Why are Ti-3Al-5Zr- Si / B composites so brittle being in as-cast state?**
2. **Why do Ti-3Al-5Zr- Si / B composites get acceptable plasticity after hot plastic deformation?**

via study of features of structure and fracture micromechanisms.

Materials

Alloys:

- Binary Ti-Si based on iod. Ti and BT1-0
- Ti – 3Al – 4Zr + 2; 4; and 6 wt.% Si
- Binary and complex Ti-B and Ti-B-Si
  - casting:
    - ingots - Æ 60 mm, length - 150 mm
  - deformation:
    - forging - for ~90% at ~1100 °C

Technical titanium alloy
BT1-0 is a base of
Ti-Si / B-X developments

Chemical composition:

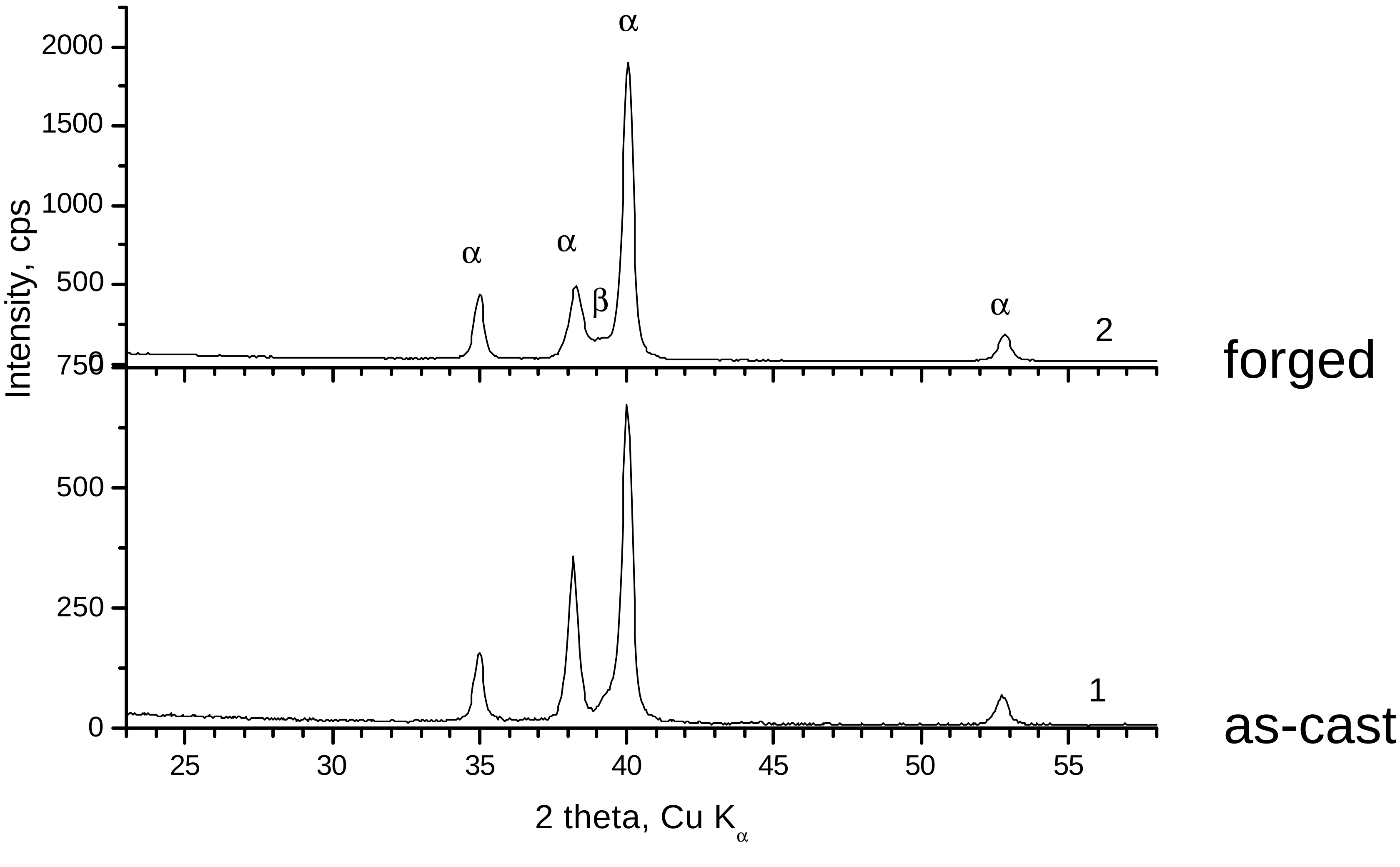
Ti – Al < 0.3; Si < 0.1; Fe < 0.25;

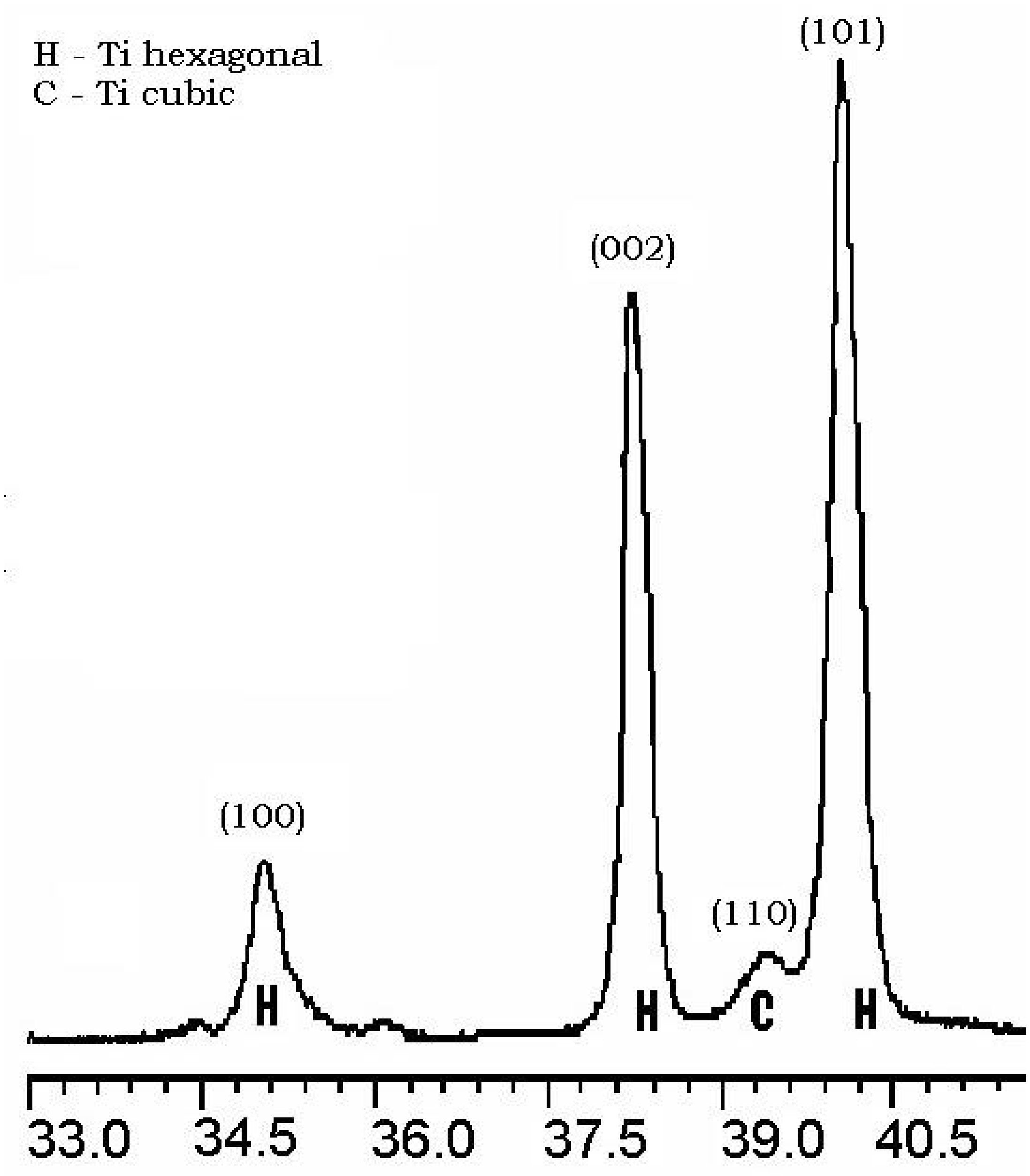
C < 0.07; N < 0.04; O < 0.2;

Others < 0.3 wt.%

X-ray spectrum of BT1-0 alloy

Ti - Fe<0.25; Si<0.1; C<0.07; N<0.04; O<0.2; others<0.3 wt.%





X-ray spectrum of titanium alloy BT1-0

Al<0.30

Fe<0.25

Si<0.10

C<0.07

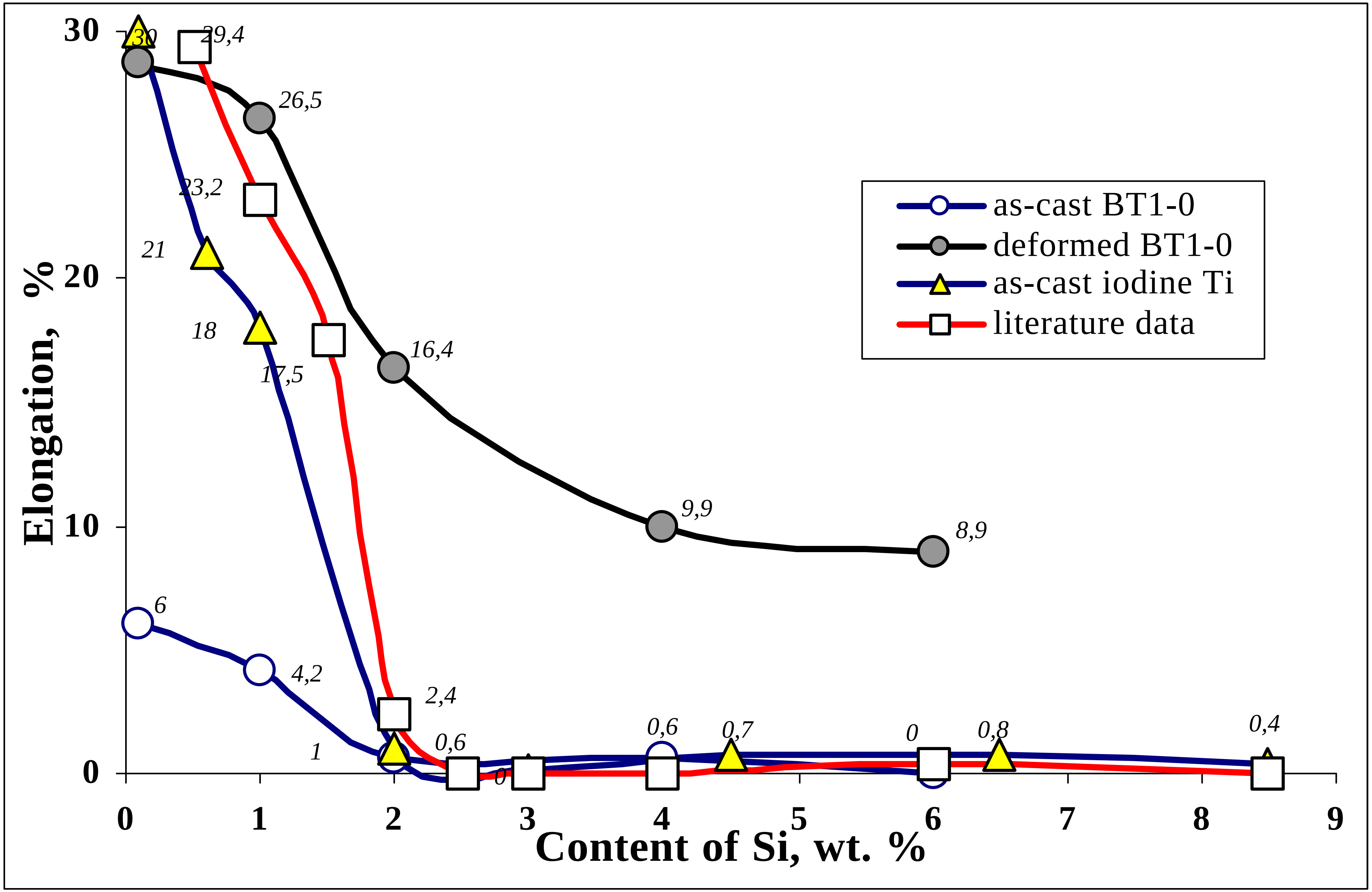
N<0.04

O<0.20

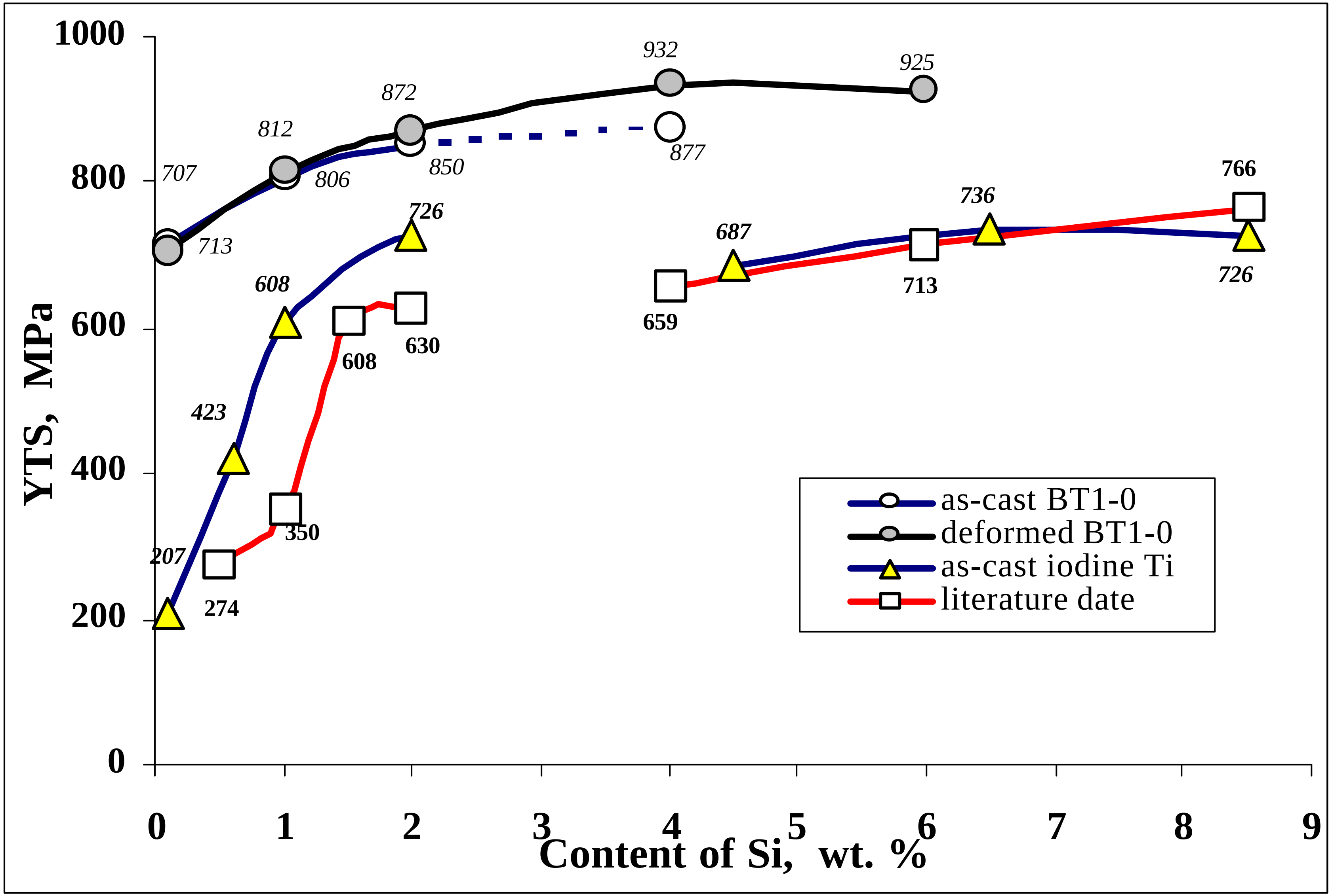
Others < 0.3 wt.%

As-cast

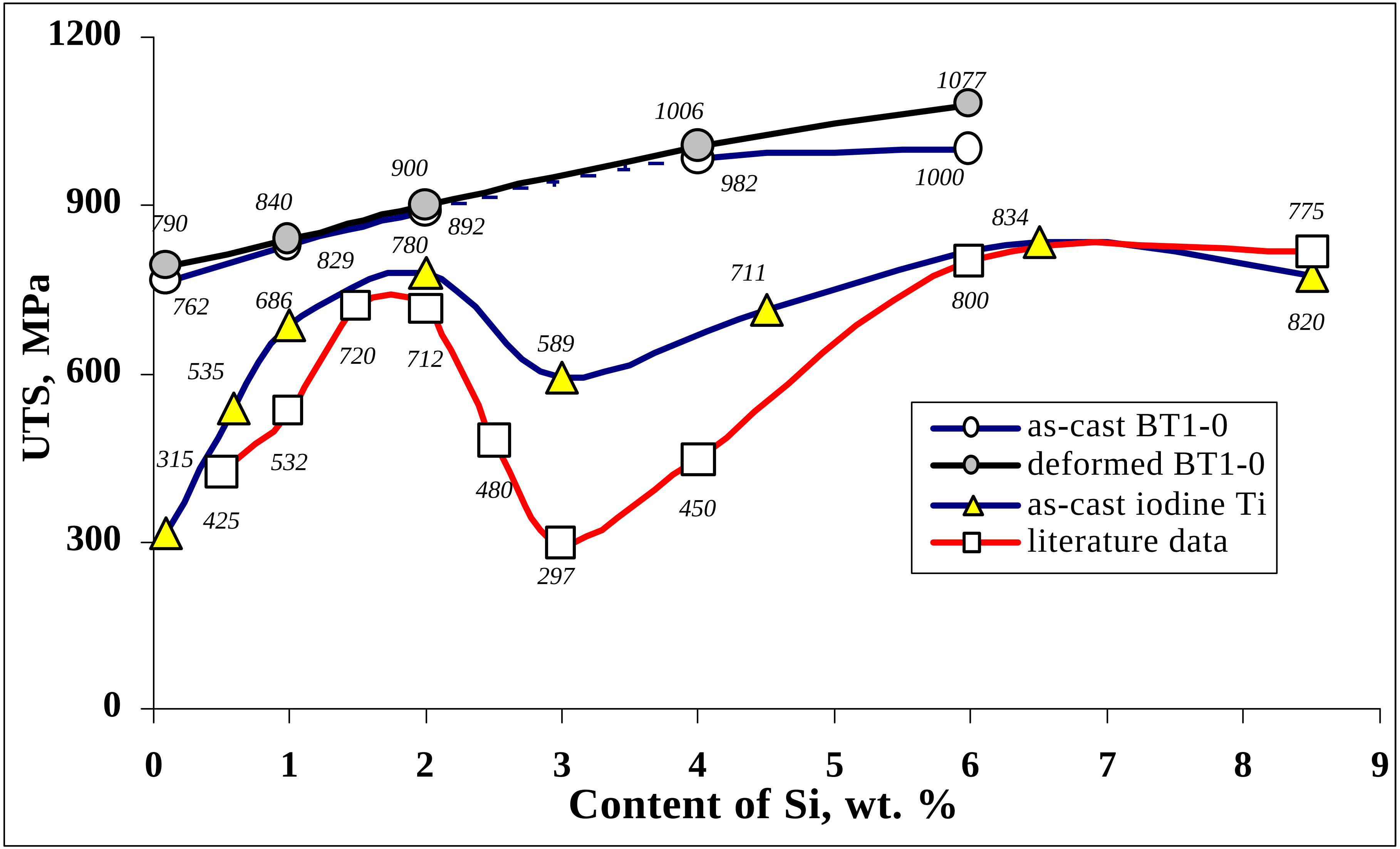
Plasticity of Ti-Si alloys



Yield strength of Ti-Si alloys



Strength of Ti-Si alloys



Binary Ti-Si system: Conclusions /1

- Alloying titanium with silicon is influencing on structure of as-cast alloy. Interval of silicon content 2-3-wt.% is critical. The exact value of the critical silicon content depends probably on additional additives and solidification history of ingots. Under the critical amount of silicon Ti-Si-alloy solidifies with formation of polygonal granular structure with decreasing grain size at increase of silicon content. At higher silicon content structure of the Ti-Si-alloys is dendritic-eutectic one with the titanium-silicide eutectic between dendrites.

Binary Ti-Si system: Conclusions /2

- Alloying titanium with silicon is embrittling it decreasing the room temperature ductility of as-cast state up to zero at critical silicon content.
- The most probable reason of such drastic decreasing of plasticity of as-cast titanium with silicon is a change of modes of formation of final structure of cooled as-cast metal at critical 2-3-wt.% value of silicon.

Binary Ti-Si system: Conclusions /3

- Fracture mechanism of the Ti-Si-alloy at the critical content of silicon in it is intergranular one resulting in both zero plasticity and significant decrease of yield strength and ultimate tensile strength in alloy based on pure titanium.

Binary Ti-Si system: Conclusions /3

- Hot deformation suppresses the negative effect of critical (2-3-wt.%) content of silicon resulting in an increase of room temperature ductility of alloy from zero to ~16 % and keeping it on level not less 9 % at higher silicon content.

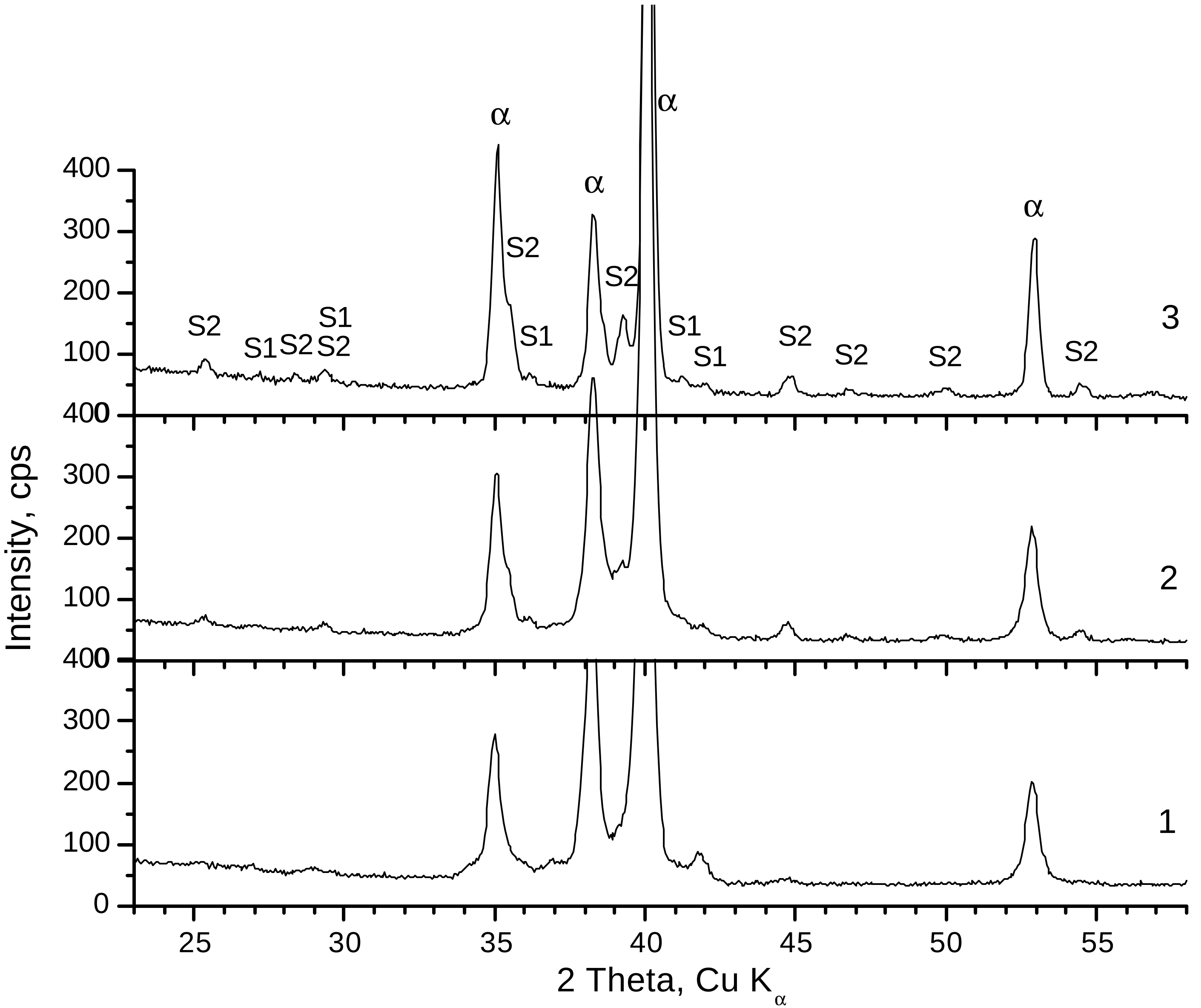
  The reason of this phenomenon is plastifying of solid solution from silicon that results in a change of fracture micromechanism from mixed cleavage + void coalescence fracture mode in as-cast state for only void coalescence in deformed state.

  Yield stress and tensile strength are enhanced with plastic deformation too.

Compositions of studied Ti-3Al-5Zr-2;4;6Si composites in as-cast and forged states

Alloy and its state		*Content (wt.%)*				
Name	[1] *of ingot*	*C*	*O*	*Al*	*Si*	*Zr*
+2Si, as-cast	*60-2-04*		0.018	3.1	2.0	4.8
+2Si, forged	*60-2-02*		0.022	2.9	2.0	5.1
+4Si, as-cast	*60-4-16*	0.24	0.023	3.4	3.9	5.2
+4Si, forged	*60-4-21*	0.25	0.022	3.0	3.6	4.8
+6Si, as-cast	*60-6-30*	0.22	0.028	3.4	6.2	4.8

X-ray spectrum of Ti-3Al-5Zr-2Si based on BT1-0

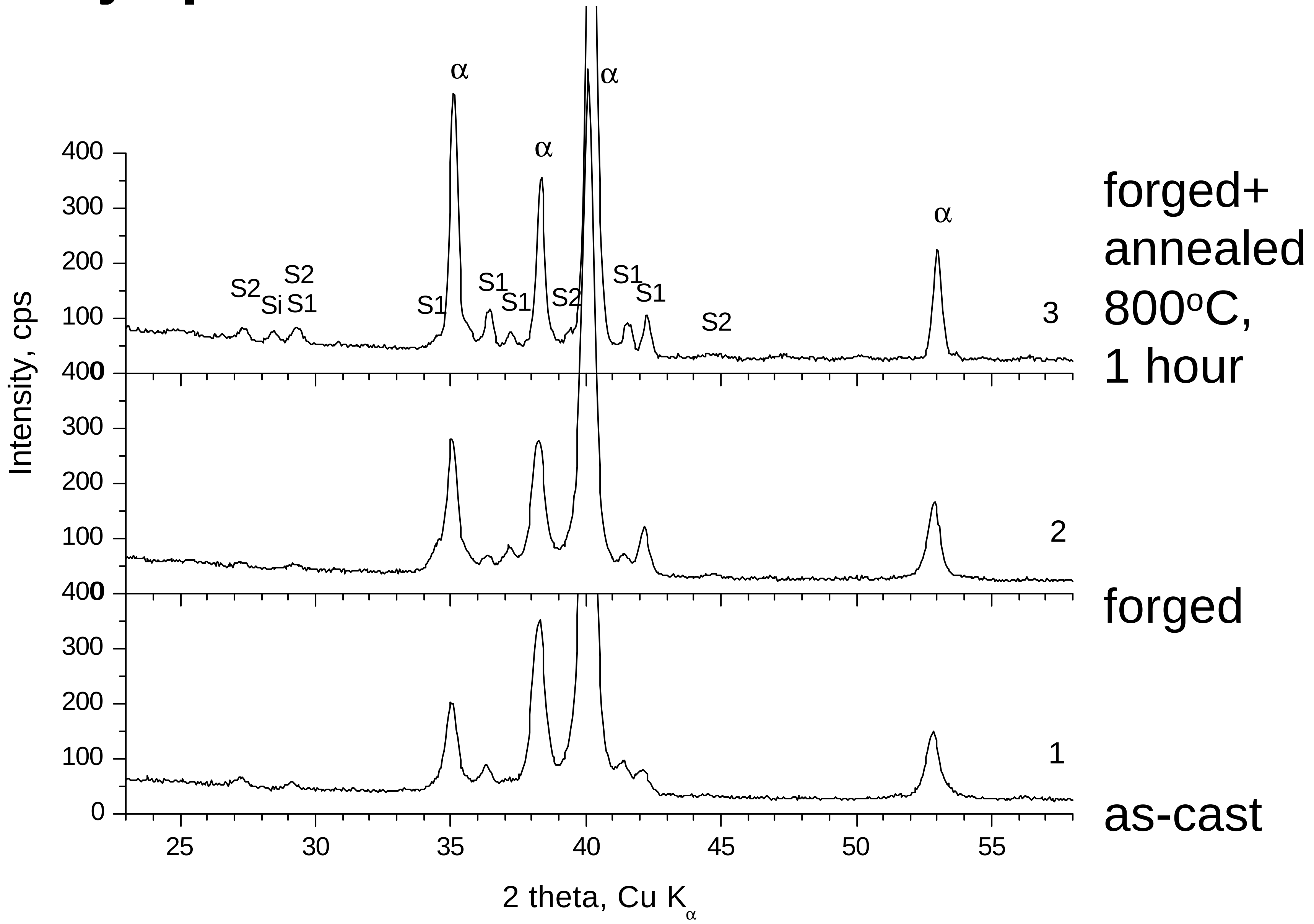


forged+ annealed 800°C, 1 hour

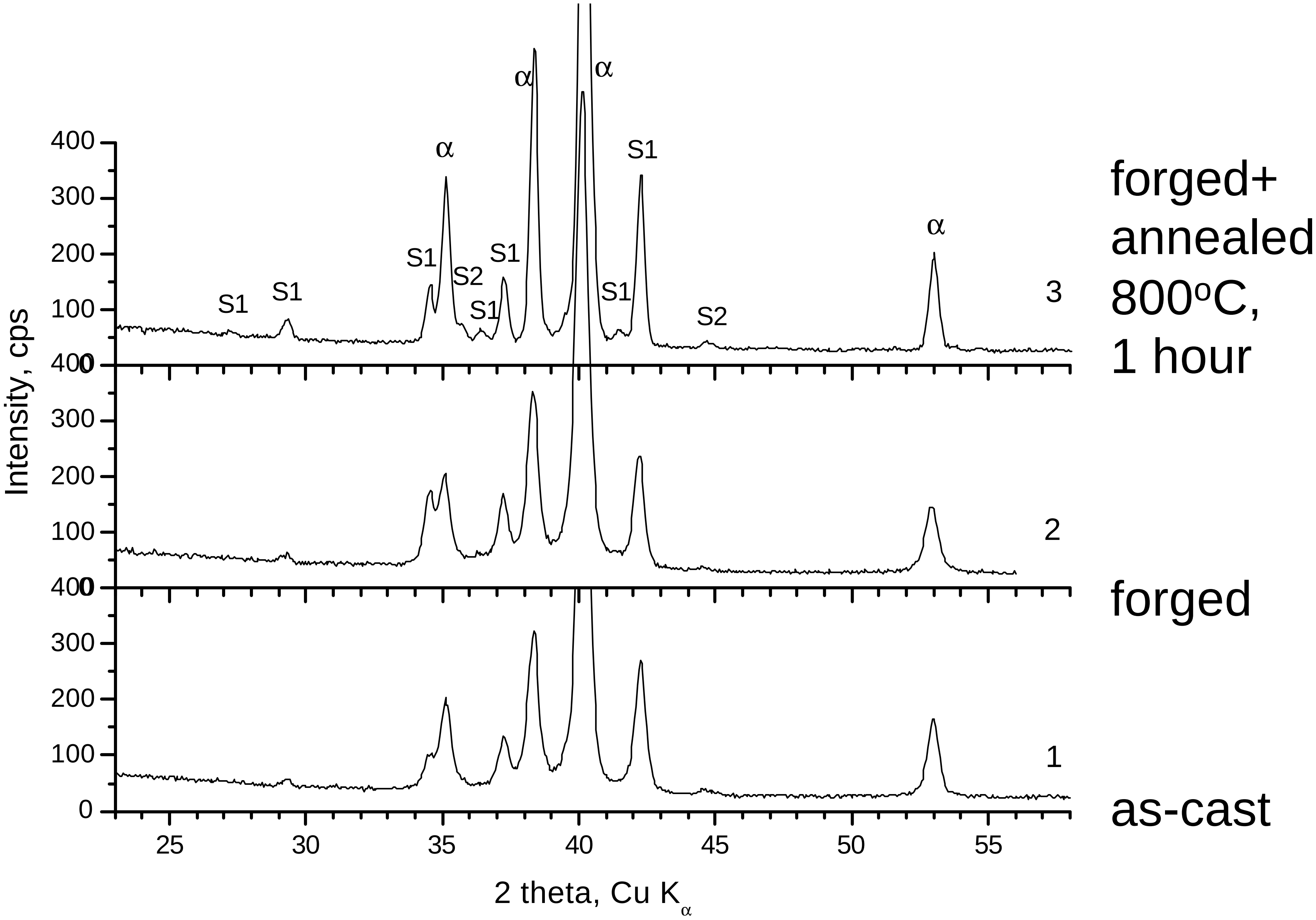
forged

as-cast

X-ray spectrum of Ti-3Al-5Zr-4Si based on BT1-0



X-ray spectrum of Ti-3Al-5Zr-6Si based on BT1-0



Additional to α'-titanium phases in Ti - 3Al - 5Zr - 2; 4; 6Si -alloys

based on BT1-0

Ti - Al<0.3; Si<0.1; Fe<0.25; C<0.07; N<0.04; O<0.2; others<0.3 wt.%

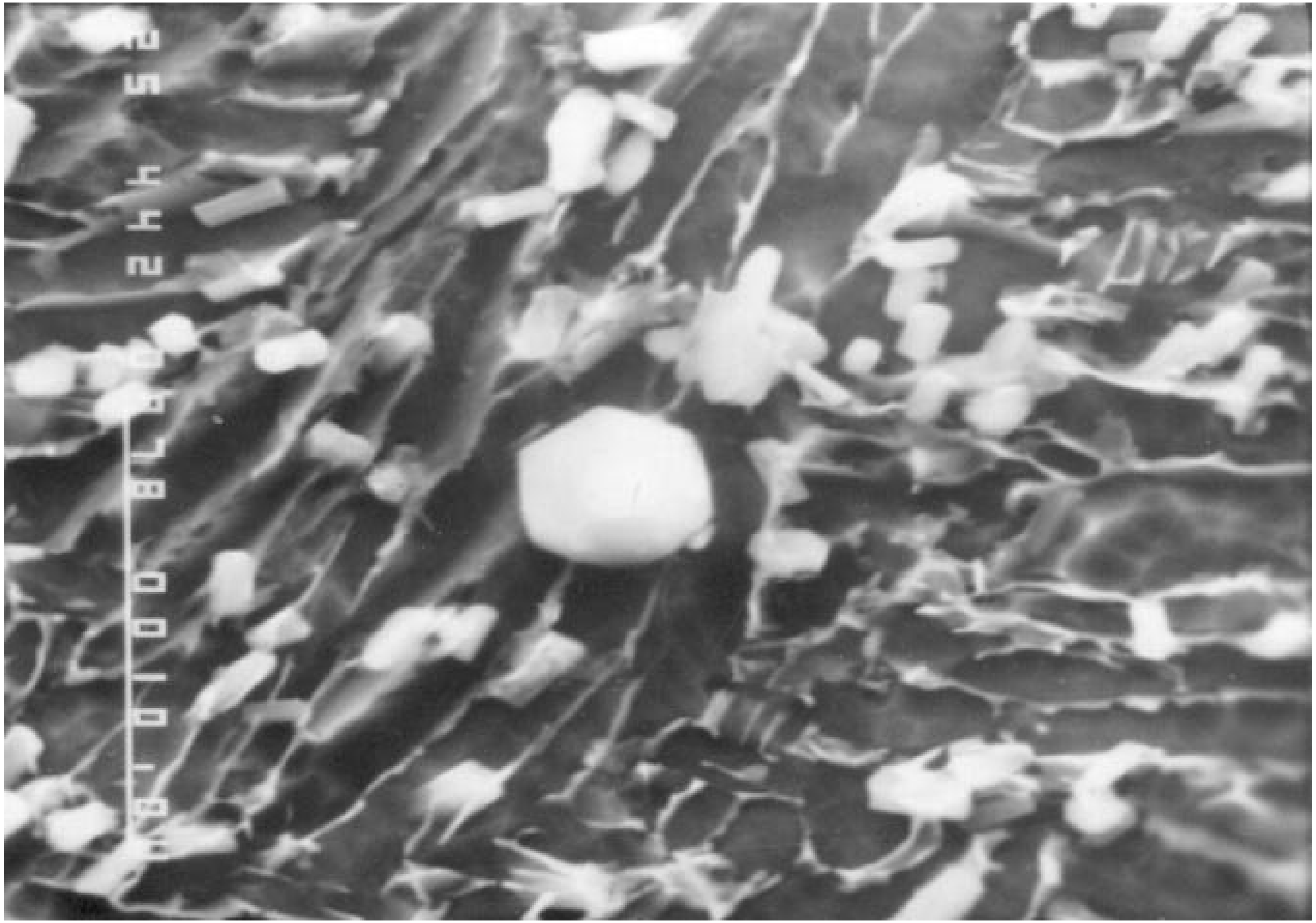
		Phases		
Alloy	State	Ti_5Si_3	Ti_2Si	β–Ti
BT1-0	as-cast	-	-	1.0-1.2
	forged	-	-	1.6-1.8
	anneal			

		Phases		
Alloy	State	Ti_5Si_3	Ti_2Si	β–Ti
+4Si	as-cast	9.6-14.4	0.6-1.0	+
	forged	8.8-13.2	2.0-2.6	1.0-1.2
	anneal	7.7-11.5	2.0-2.6	+

		Phases		
Alloy	State	Ti_5Si_3	Ti_2Si	β–Ti
+2Si	as-cast	4.4-4.6	1.6-2.4	+
	forged	0.4-0.6	5.0-6.5	+
	anneal	0.4-0.6	6.0-8.4	+

		Phases		
Alloy	State	Ti_5Si_3	Ti_2Si	β–Ti
+6Si	as-cast	11.2-16.8	1.5-2.2	+
	forged	12.8-19.2	1.6-2.3	+
	anneal	13.6-20.4	2.1-2.7	+

SEM structure of forged Ti-3Al-5Zr-2Si- alloy

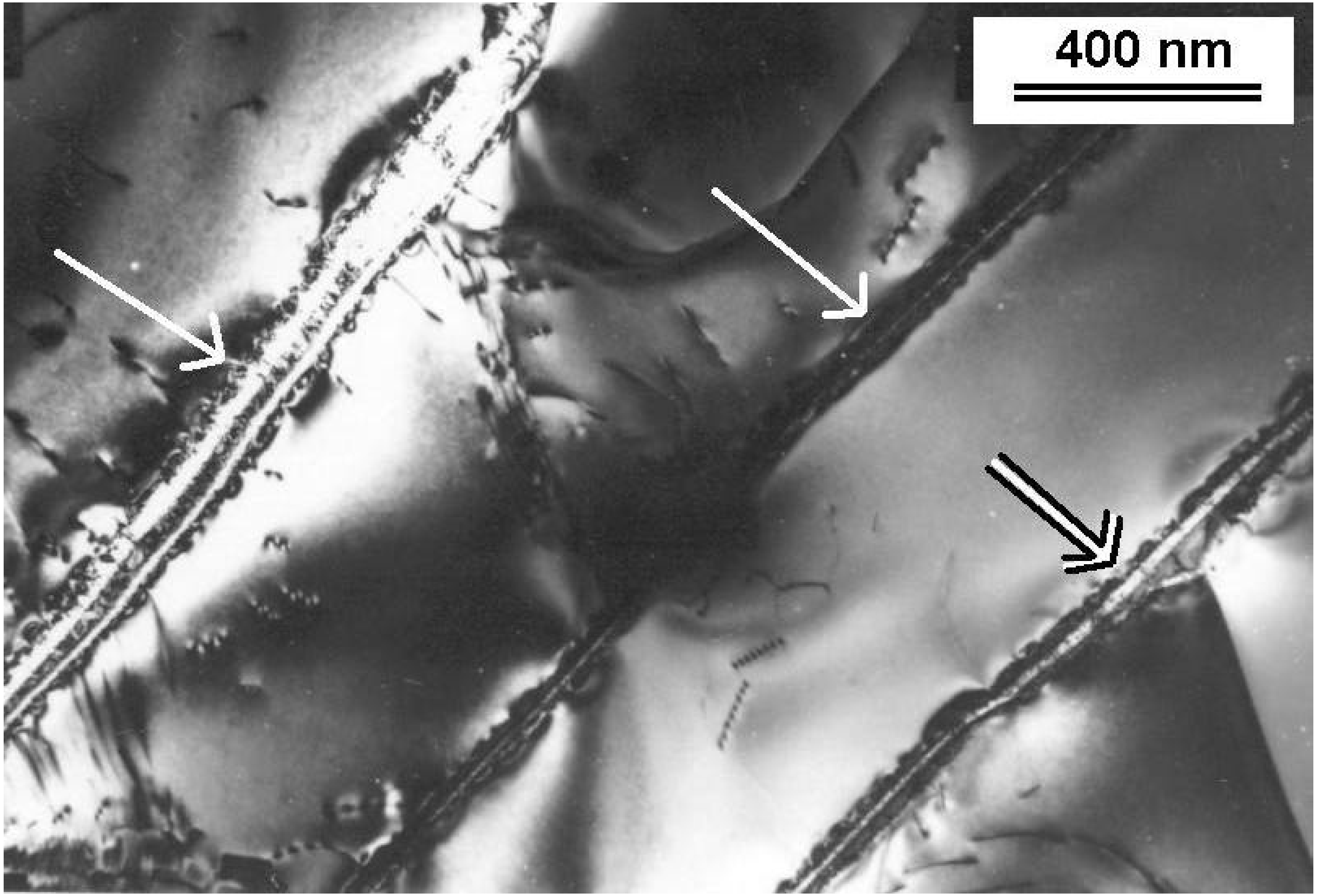


Composition of phases in as-cast Ti-3Al-5Zr-2Si alloy

Name of phase		*Chemical element*			
		Al	**Si**	**Zr**	**Fe**
Matrix of a'-lamellas,	**wt.%**	**3.2 ¸ 3.3**	**0.6 ¸ 1.3**	**2.1 ¸ 3.4**	**0.03 ¸ 0.04**
b-Interlayers,	**wt.%**	**2.4 ¸ 2.8**	**1.1 ¸ 3.6**	**2.9 ¸ 7.8**	**0.1 ¸ 0.5**
Second. silicides, $(Ti,Zr)_x(Si,Al)_y$	**wt.%**	**2.3 ¸ 2.7**	**1.7 ¸ 4.3**	**4.2 ¸ 8.9**	**0.04 ¸ 0.1**
	***at.* %**	*4.1 ¸ 4.8*	*2.9 ¸ 7.4*	*2.2 ¸ 4.7*	*0.04 ¸ 0.08*
Eutectic silicides, $(Ti,Zr)_5(Si,Al)_3$	**wt.%**	**0.7 ¸ 1.8**	**7.0 ¸ 23.9**	**6.6 ¸ 28.0**	**0.1 ¸ 0.4**
	***at.* %**	*1.2 ¸ 3.2*	*11.8 ¸ 35.7*	*3.1 ¸ 15.1*	*0.08 ¸ 0.16*
Matrix between eutectic silicides,	**wt.%**	**2.8 ¸ 3.1**	**0.5 ¸ 0.6**	**1.2 ¸ 1.9**	**0.01 ¸ 0.04**

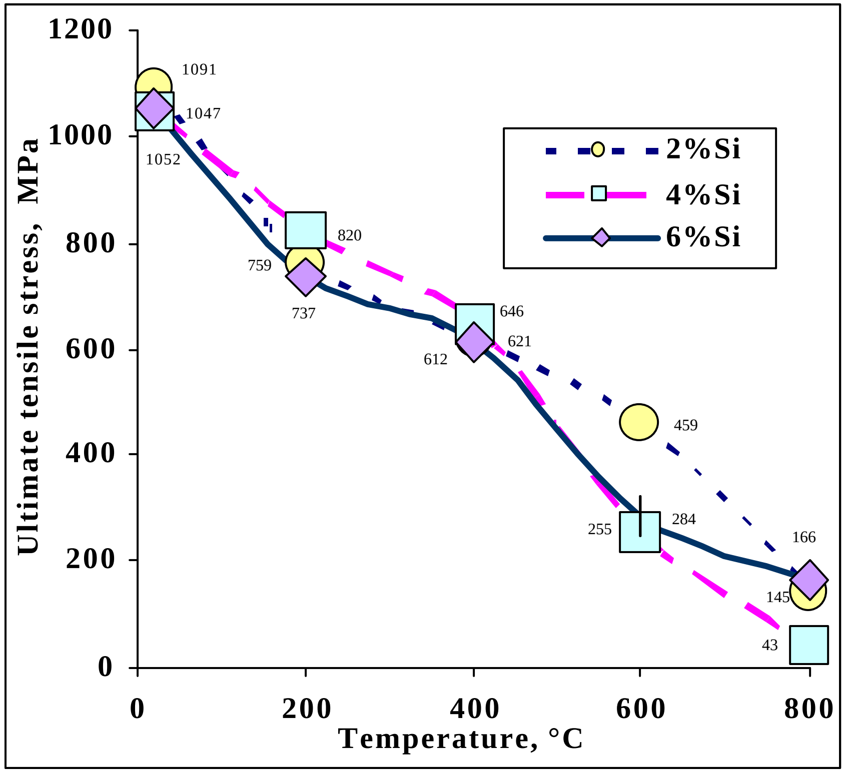
Data of XRMA of thin TEM samples with Superprobe-733

TEM structure of forged Ti-2Si-3Al-5Zr alloy with b-phase

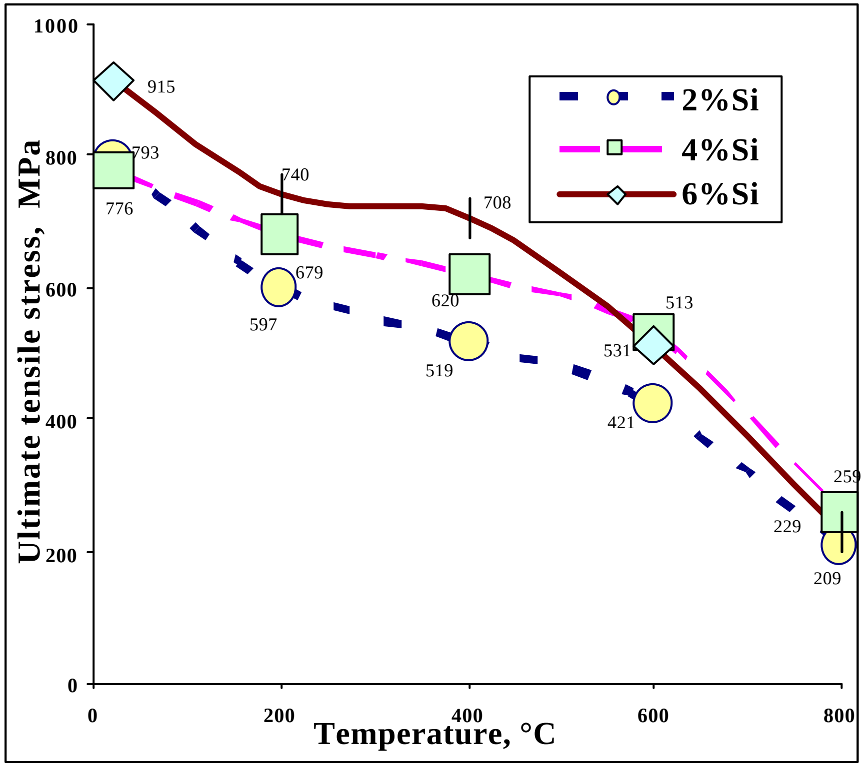


Strength of Ti-3Al-5Zr-2;4;6Si

as-cast

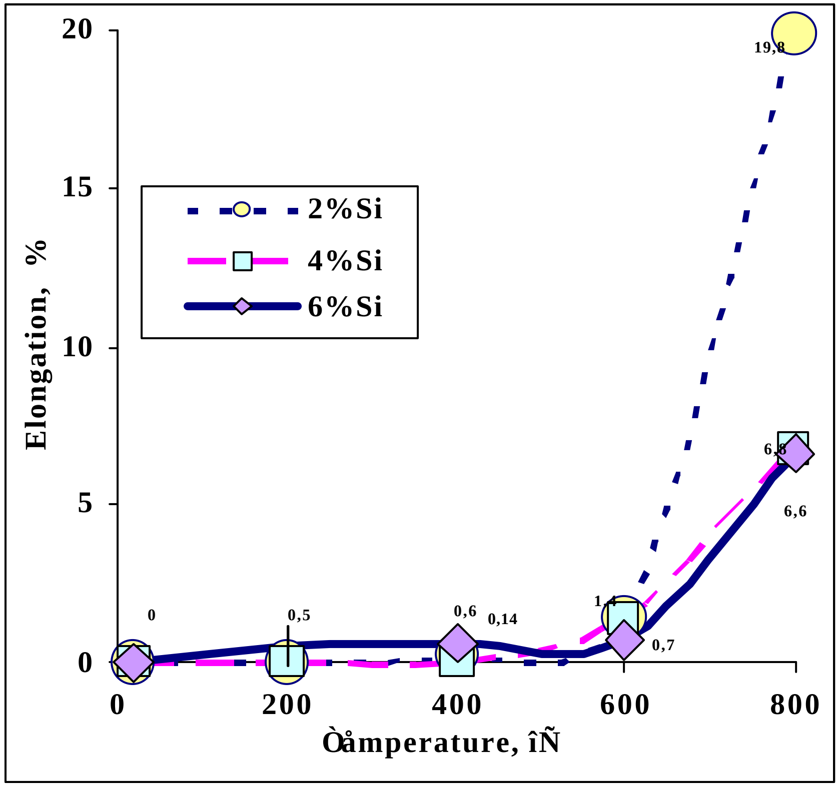


forged



Plasticity of Ti-3Al-5Zr-2;4;6Si

as-cast



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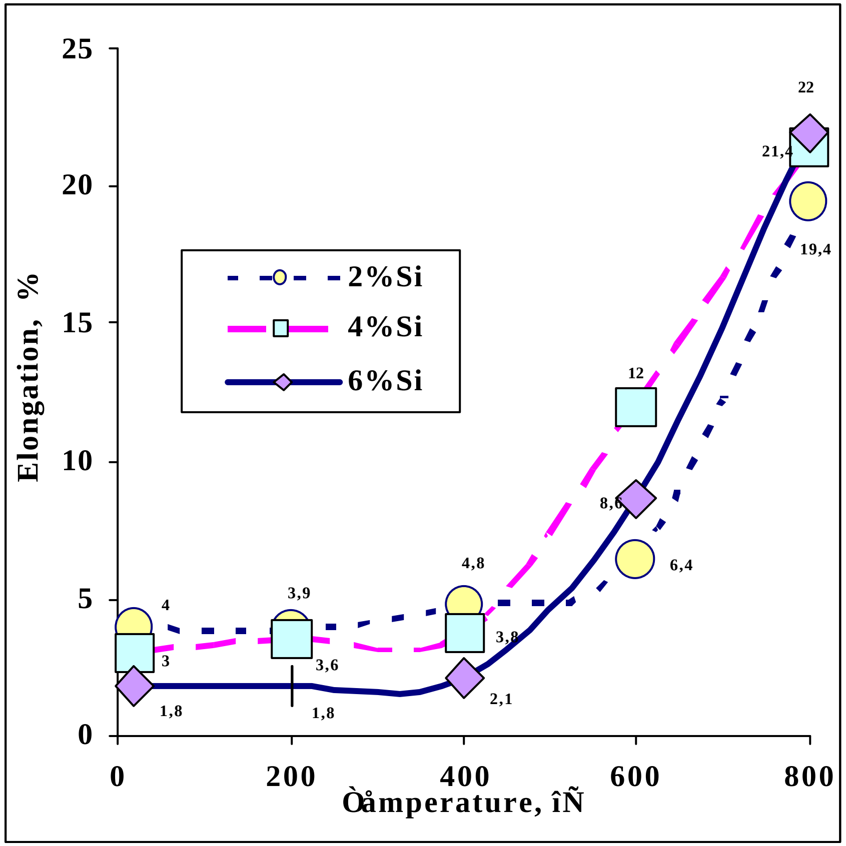
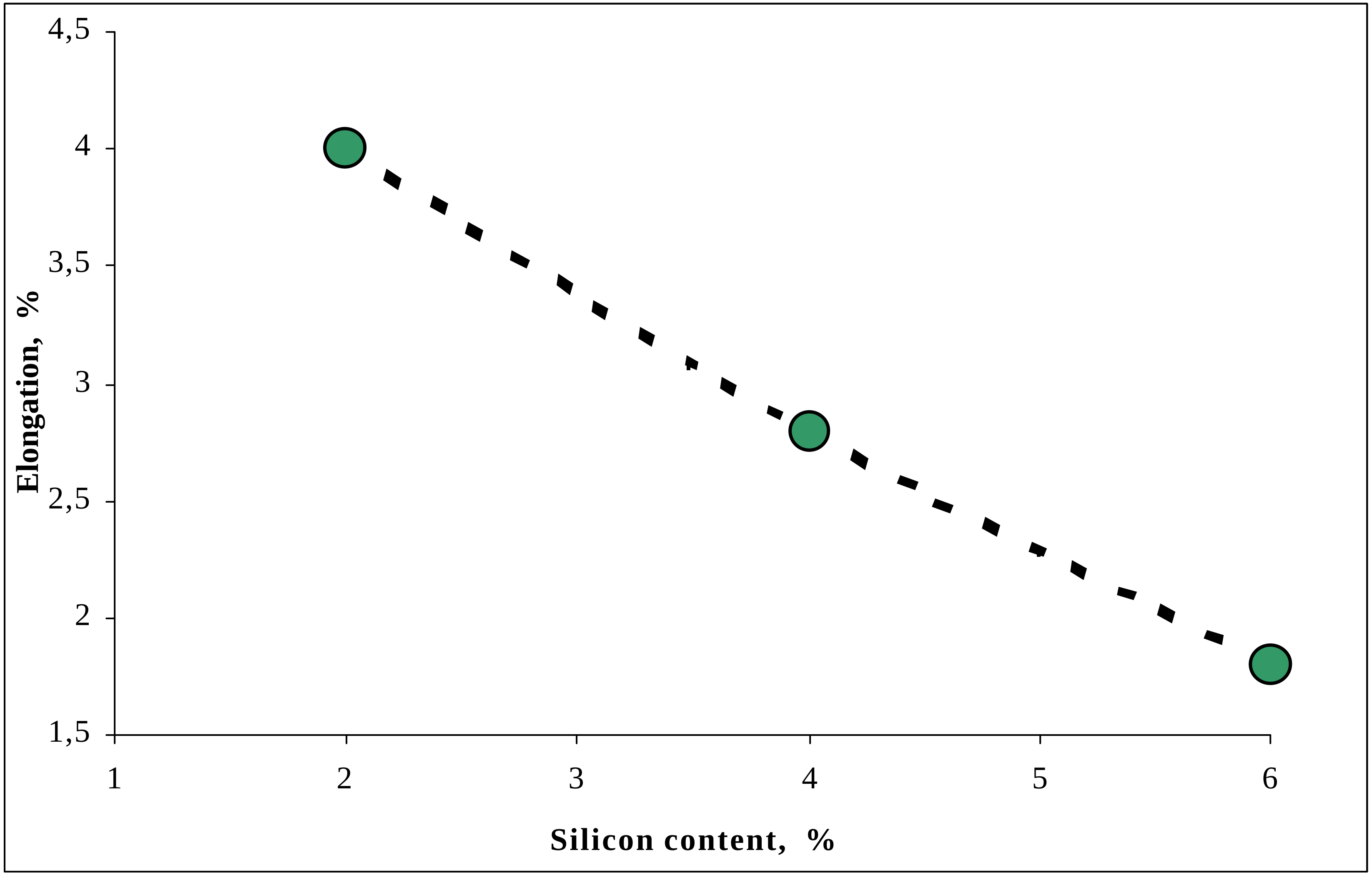


experimental results and their discussion

Fracture mechanisms of as-cast Ti-3Al-4; 6Si-5Zr alloy

- Transgranular pore coalescence and microfragmented cleavage at RT – 600 °C;
- Ductile (with pores coalescence) fracture of eutectic interdendritic layers;
- Subcritical crack growth with pores coalescence of ~130 μm length at RT;
- "Fractographic" fracture toughness is equal to 15.5 $MPa \cdot m^{1/2}$.
- Direct fracture toughness measurement with standard method has given 15.35 $MPa \cdot m^{1/2}$.

Plasticity of forged Ti-3Al-5Zr vs silicon



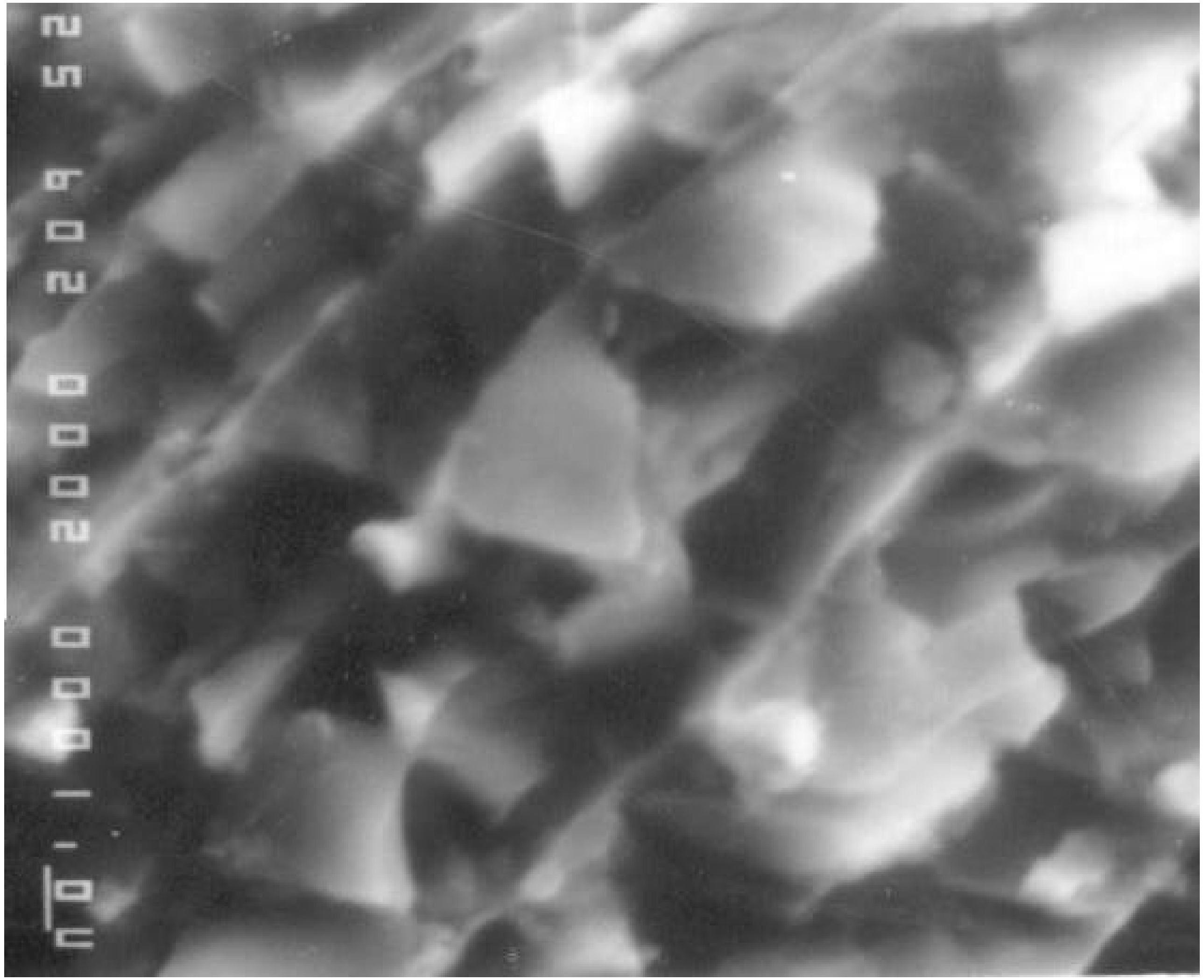
experimental results and their discussion

Fractographical features of as-cast Ti-3Al-4Si-5Zr alloy

For the first time it were observed:

- ★ Microcracking of hexagonal acicular a-grains with triangular and hexahedral fragments.
- ★ Ductile "knife-like" fracture of interacicular a-granular b-phase.
- ★ Subcritical (stable) crack growth with pores coalescence and cleavage microcracking.

Cleavage microcracking of body of A-lamellas and knife fracture of interlamellar b-phase in Ti-3Al-5Zr-4Si alloy



Conclusions /1

Joint data of structural and fractographic researches show that

- Ti-3Al-4Zr alloy containing 2, 4 and 6 wt. % Si in both as-cast and deformed states has complicated heterogeneous structure having both typical for α-titanium alloys acicular α-colonies with β-phase between α-grains, particles of secondary silicides of solid solution decomposition and interdendritic eutectic Ti-$(Ti,Zr)_5Si_3$.
- High temperature plastic deformation leads to arising the $(Ti,Zr)_2Si$ silicide.

Conclusions /2

- Ti *in situ* composites studied demonstrate typical brittle-to-ductile behavior.
- The transition of as-cast and deformed states in a ductile state occurs in a wide temperature interval occupying a few hundreds of degree centigrade.
- Their upper temperature limits of both as-cast and deformed states are near 600 °C.
- The lower temperature limits of as-cast and deformed states are significantly below room temperature.

Conclusions /2a

As to the lower temperature limit it is significantly below room temperature because in spite of near zero plasticity fractography points out a significant part of samples, which fails with ductile pore coalescence, evidencing the <u>high plastic potential</u> of materials.

Conclusions /3

Fracture mechanisms in temperature range room temperature RT - 400-600 °C are

- Intensive microcracking by cleavage both matrix and phase.
- Ductile coalescence of small pores. Only intergranular and inter α-grain layers fail with this mechanism.
- Layers between acicular α-grains that is β-phase fail in a ductile way forming knife-like fracture.

Conclusions /6

- The stage of subcritical crack growth may be distinguished in Ti-3Al-4Si-5Zr alloy.
- Fracture toughness at RT that might be estimated at fractographical study is around 15.5 $MPa \cdot m^{1/2}$.
- Direct fracture toughness measurement with standard methods gives 15.35 $MPa \cdot m^{1/2}$.

Conclusions /7

As-cast alloy with 2 wt. % Si fails with

- interdendritic way but with ductile pore coalescence under temperatures up to 700 °C. Pores are nucleated near particles of intergranular silicides.
- Preliminary plastic deformation of this alloy suppresses low temperature ductile intergranular fracture allowing plastic intragranular fine pore coalescence at RT even.
- Ductile fracture at temperatures above 700 °C takes place with formation of typical dimple fracture and some marks of dynamic recrystallization.

Conclusions /5

- Adhesion of silicides with matrix is high resulting in that even large particles does not separate from matrix.
- In general, increasing silicon content results in
  - homogenizing fracture surface,
  - suppressing interdendritic fracture, and
  - ductile fracture with pores coalescence and brittle one with cleavage.

Ti-3Al-5Zr-xSi: Conclusions - 4

- The Ti *in situ* composites studied demonstrate typical brittle-to-ductile behavior.
- The transition of as-cast and deformed alloys into a ductile state occurs in a wide temperature range occupying a few hundreds of degrees centigrade.
- Their upper temperature limits of both as-cast and deformed states are in a range of 600 °C.
- The lower temperature limits of both as-cast and deformed states are significantly below room temperature.

Ti-3Al-5Zr-xSi: Conclusions - 5

- Bonding of silicides with matrix is extremely high.
- They are not separated from matrix at all the levels of deformation applied.

Ti-3Al-5Zr-xSi: Conclusions - 6

Fracture micromechanisms of as-cast state are as follows:

In temperature range from room temperature to 400-600 ºC they are:

- Microcracking by cleavage both matrix and eutectic silicides.
- Ductile void coalescence. However only eutectic matrix and inter α'-lamellar β-layers fail with this mechanism.
- Because of alloys containing ~2-wt. % Si have a simple polycrystalline form they fail with ductile intergranular mode.

Ti-3Al-5Zr-xSi: Conclusions -7

Fracture micromechanisms of deformed state:

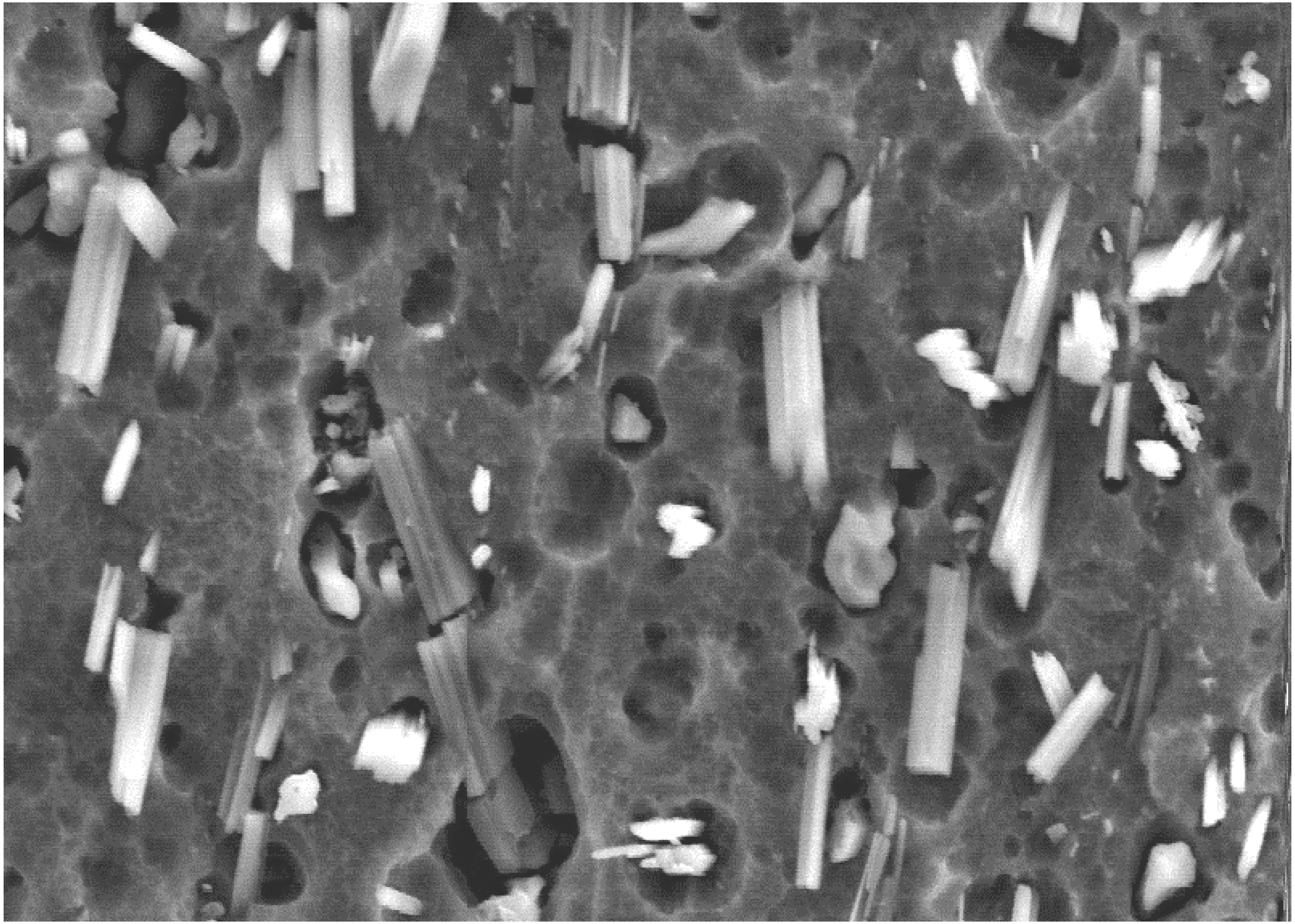
At temperatures above room temperature they are:

- pore coalescence with small dimples arising at particles and in solid solution,
- small portion of cleavage microcracking.

Properties of Ti-B-alloys: RT

	Ti-1.6B	*Ti-5.5Al-1.9B*	*Ti-6.6Al-3.5Zr-1.3Si-1.1B*
Yield strength, MPa	**944**	**1140**	**1469**
Strength, MPa	**977**	**1184**	**1530**
Elongation, %	**6.4**	**6.24**	**1.4**
Young modulus, GPa	**136**	**152**	**158**
Fracture mechanism	***void coalescence***		

Structure of forged Ti-3.5Al-5Zr-1.3B-1.1Si alloy. SEM



Chemical composition of matrix and borides in deformed Ti-3Al-5Zr-1.2Si-1.1B -alloy

	Al	**Zr**	**Si**	**Fe**	**Others**
matrix	**+**	**+**	**+**	$\approx$**0**	$\approx$**0**
boride	**+**	**+**	**+**	**+**	**B, O, C, S, P**

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